LA-UR-22-20990

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Title: Understanding the Origin of the Hadron Mass within the Standard Model

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Intended for: LDRD ER preproposal

Issued: 2022-02-07

Objective

Understanding the origin of the hadron mass, which constitutes 99% of our visible universe, is one of the central goals of nuclear physics. Although the Higgs mechanism provides mass for the fundamental building blocks of matter, it can only contribute less than 2% of the proton mass. The vast majority of the proton mass is believed to come from the strong force that tightly binds quarks and gluons (collectively called partons) together as described by Quantum Chromodynamics (QCD). The mass that emerges as a consequence of the strong interactions within QCD is commonly denoted as **Emergent Hadronic Mass** (EHM). Understanding how the nucleon mass emerges in QCD is a prerequisite to an explanation of how the Universe came into being, therefore it is of utmost importance and one of the key questions to be addressed by the future Electron-Ion Collider (EIC) [1, 2]. When it comes to light mesons, particularly pions, the mass decomposition is drastically different. Since the pion is naturally massless in the chiral limit [3, 4], the majority of its observed mass needs to come from other mechanisms within QCD [5]. Any successful explanation for the EHM needs to be able to reconcile both the heavy proton mass and the very light pion mass (~15% of proton mass) simultaneously. The EHM theories have direct measurable implications on the description of the internal structure of the hadron [6], i.e., how the partons distribute inside the hadron. Precise measurement of the parton distribution functions (PDFs) will provide necessary experimental verifications and constraints of potential EHM mechanisms.

We propose to carry out a comprehensive study of the poorly known pion PDFs at the AMBER experiment at CERN. The measurement will provide vital input to constrain the global analysis of the pion PDFs, which are still based on limited data obtained more than 30 years ago. The proposed pion measurement is the only direct measurement achievable within this decade, which could lead to a future major meson structure program parallel to the EIC's proton structure measurement.

Problem and Proposed Innovation

In contrast to the abundant experimental measurements of the quark and gluon distributions inside the nucleon, there have been only very scarce data available for the light meson structures [7-10]. In particular, pion's parton distributions, which constrain the EHM phenomenon in QCD on a much smaller energy scale, are especially limited and outdated. In this project, we propose to perform a detailed study of the pion structure through the pion-induced Drell-Yan (DY) and charmonia production to map out the distributions of the valance quark, sea quark, and gluon inside the pion. Unlike the EIC where the pion structure is probed via the off-shell virtual pions created by the neutron-tagged Deep Inelastic Scattering (DIS) process, the DY process provides the most direct and model-independent access to the quark distributions inside the physical pion. Charmonia production on the other hand provides an alternative probe to investigate the structure of the pion. At relatively low fixed-target energies, both quark-antiquark annihilation and gluon-gluon fusion process contribute to the production of different charmonia states (J/ψ and $\psi(2S)$), therefore allowing simultaneous access to both quark and gluon distributions of the beam particle. A unique opportunity for such a study is provided by the high-intensity pion beam from the CERN M2 beamline and the AMBER experiment [11]. The AMBER experiment has been approved for its phase-1 running plan, which includes two years of data taking between 2025 and 2027.

The spectrometer of AMBER is largely based on the same spectrometer from its predecessor, the COMPASS experiment, as shown in Fig. 1, with the proposed modifications of the target bunker enlarged on the top. The multiple scattering and energy loss of the muons (from DY and Charmonia decays) in both target and the absorber further downstream significantly degrade the reconstructed dimuon kinematic resolution. Such large smearing effects were observed in the COMPASS analysis, which lead to very poor dimuon mass and production vertex resolution. Fig.

2(a) shows the dimuon mass spectrum obtained by COMPASS using the same spectrometer [12]. The poor vertex resolution caused large contamination from the open-charm and other combinatorial background as well as the tail of the charmonia resonances in the high mass region. Very tight event selection criteria had to be adopted which resulted in much-reduced statistics and large uncertainty in the transverse spin asymmetry measurement in the DY process [12]. Furthermore, even though the shoulder from the $\psi(2S)$ resonance was clearly observed, the limited mass resolution caused the tail from the J/ψ to completely overwhelm the $\psi(2S)$ sample and made the $\psi(2S)$ analysis impossible.

Therefore, in order to minimize the backgrounds and maximize the signals of the DY and the J/ψ, and to access the $\psi(2S)$ production, an active vertex tracking detector is needed between the target stations and the hadron absorber to provide a clean separation of collision vertices between different target stations, as well as the kinematic reconstruction with minimal distortion.

R&D Methods and Anticipated Results

To mitigate the low resolution of the existing AMBER spectrometer, we propose to reuse the parts from the decommissioned Forward Silicon Vertex Tracker (FVTX) from the PHENIX experiment [13] to build a silicon-strip vertex tracker for AMBER. The $5M FVTX detector was designed and built by LANL. It was installed in 2012 and decommissioned in 2016 after PHENIX completed its last run. Other than the backend electronics, the rest of the detector, including the sensors, frontend ASICs, mechanical supporting disks, and cooling system are available to us. Due to the low radiation environment at PHENIX and short running time, the detector has been only lightly used and is still fully functioning. We propose to adapt the existing FVTX to build a similar vertex tracker for AMBER. The availability of the parts, design, and intimate knowledge base at LANL of the existing detector not only greatly reduces the cost but also the technical and schedule risks for the proposed detector, compared with other vertex detector options of a similar scale.

Monte-Carlo studies indicate that significant improvement in both vertex and mass resolution can be achieved. The much-improved vertex reconstruction can separate the muons from different target cells, which completely recovers the efficiency loss due to the target geometry requirement and significantly reduces the possibility of having two uncorrelated muons misidentified as a signal dimuon. Overall, the signal to background ratio of the DY events will be improved by a factor of 4. Fig. 2(b) shows the simulated dimuon mass spectrum for two years of data taking with the proposed vertex detector, where significant improvement of the mass resolution of J/ψ and $\psi(2S)$ resonances, as well as suppressed open-charm and combinatorial background can be observed.

The timing of the proposed project aligns perfectly with the beam schedule of the AMBER experiment. We will join the AMBER collaboration, spend the first two years to completely refurbish the FVTX detector, integrate the readout with AMBER's existing data acquisition system, and deliver a prototype of the proposed detector. During the third year, the prototype detector will collect data with the rest of the AMBER experiment. We will analyze the data and release the world's best direct measurement of the internal structure of the pion. After the completion of the ER, we will seek future funding to instrument the rest of detector readout during the long shutdown and commission the full detector before AMBER's second data taking in 2027.

Importance for the Laboratory and the Nation

The proposed research is in the realm of fundamental open science that aligns with lab's NPF pillar. Participation in the AMBER experiment with a critical instrumentation project will allow us to assume the leadership role in the current and future light meson structure and EHM physics program. The proposed vertex tracker, together with its readout and triggering electronics, will provide the first benchmark for a suitable precision vertex tracker candidate for the future EIC.

Figures

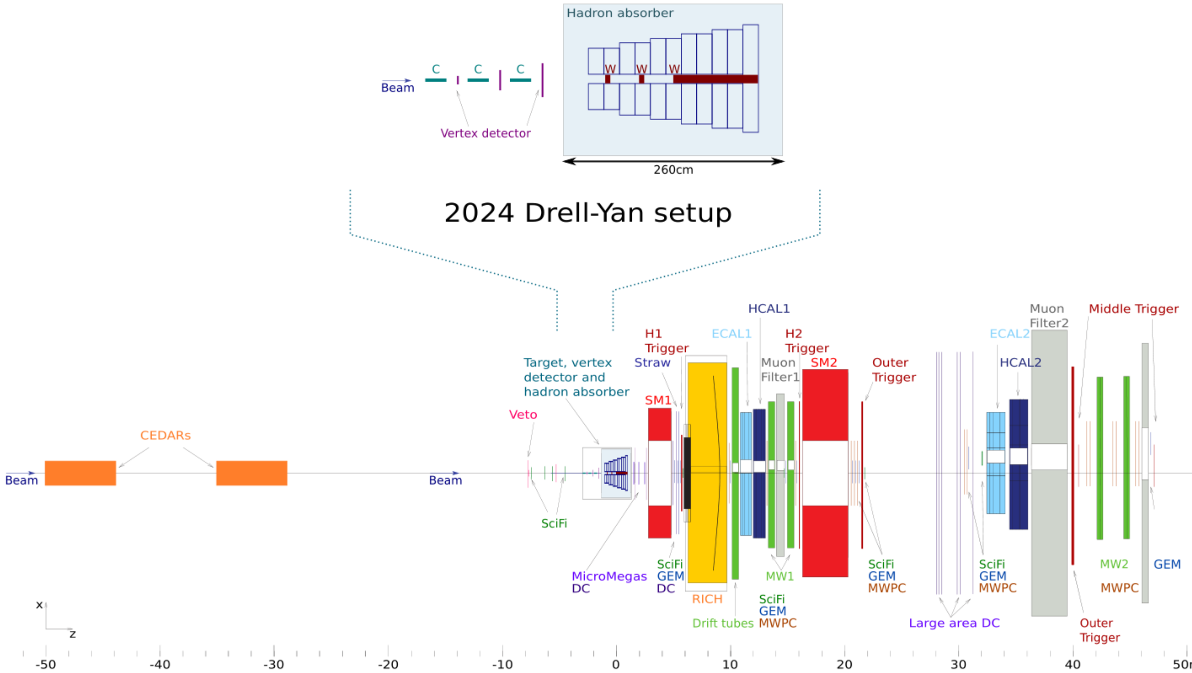

Figure 1 Experimental setup for the proposed Drell-Yan and Charmonia measurements [11]. **Top:** conceptual sketch of the target system, hadron absorber, and the proposed vertex tracker. **Bottom:** Extended setup. The beam enters from the left. The spectrometer comprises two stages built around two large dipole magnets SM1 and SM2 shown in red. The two stages are called large angle spectrometer (LAS) and small angle spectrometer (SAS), and each is equipped with tracking detectors, an electromagnetic calorimeter, a hadronic calorimeter, and a muon filter. The entire spectrometer is located immediately downstream of the target bunker which is built with concrete blocks shielding the target system and the hadron absorber.

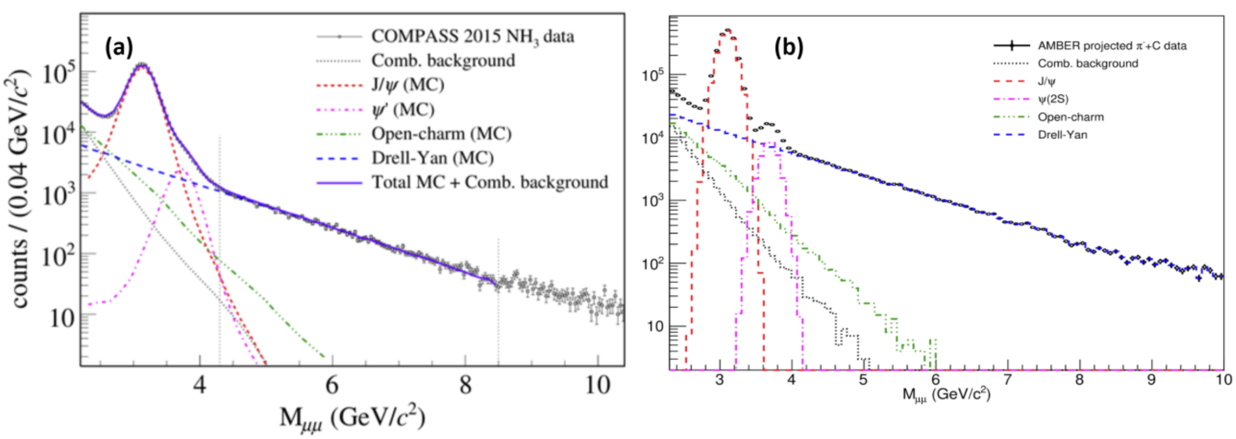

Figure 2 **(a)** Dimuon mass spectrum from the COMPASS experiment using the same spectrometer; **(b)** Expected dimuon mass spectrum from the AMBER experiment with the proposed SVTX detector included. Significant improvement of the resolution of the charmonium states and background suppression can be observed. The mass resolution for the *J/ψ* is reduced from 180 MeV/c^2 to 120 MeV/c^2. The combinatorial and open-charm background is suppressed by more than a factor of 2.

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Glossary of Acronyms

- **QCD: Q**uantum **C**hromo**d**ynamics is the theory of the strong interaction between quarks mediated by gluons, the fundamental building blocks of composite hadrons such as proton, neutron and pion.
- **EHM: E**mergent **H**adronic **M**ass. The hadron mass that emerges as a collective effect from the interactions between the quarks and gluons.
- **EIC: E**lectron-**I**on **C**ollider is the next-generation flagship facility of the US Nuclear Physics, aiming at unlocking the secrets of the strong force.
- **PDF: P**arton **D**istribution **F**unction give the probability to find a parton (quarks and gluons) in a hadron as a function of its longitudinal momentum fraction.
- **AMBER: A**pparatus for **M**eson and **B**aryon **E**xperimental **R**esearch experiment the next-generation successor of the COMPASS experiment at CERN
- **Drell-Yan (DY):** The Drell-Yan process is an electromagnetic effect in which a quark and antiquark from a pair of interacting hadrons annihilate to produce a virtual photon, which subsequently decays to a lepton pair.
- **Charmonium:** meson formed by the bound state of charm and anti-charm quarks.
- **COMPASS: C**ommon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy experiment is a multipurpose experiment at CERN's SPS beamline.
- **PHENIX: P**ioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment is an exploratory experiment at Brookhaven National Laboratory for the investigation of high energy collisions of heavy ions and protons, and is designed specifically to measure direct probes of the collisions such as electrons, muons, and photons. LANL is a collaborator of the PHENIX collaboration.
- **ASIC: A**pplication-**S**pecific **I**ntegrated **C**ircuit is a microchip designed for a special application.
- **NPF: N**uclear and **P**article **F**utures, one of LANL's science pillars.